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Correlation of Hollow Cathode Assembly and Plasma Contactor Data from Ground Testing and In-Space Operation on the International Space Station

Scott D. Kovaleski
QSS Group, Inc., Cleveland, Ohio

Michael J. Patterson and George C. Soulas
Glenn Research Center, Cleveland, Ohio

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Scott D. Kovaleski
QSS Group, Inc.
Cleveland, Ohio 44135
216–433–3735
scott.kovaleski@grc.nasa.gov

Michael J. Patterson and George C. Soulas
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Charge control on the International Space Station (ISS) is currently being provided by two plasma contactor units (PCUs). The plasma contactor includes a hollow cathode assembly (HCA), power processing unit and Xe gas feed system. The hollow cathode assemblies in use in the ISS plasma contactors were designed and fabricated at the NASA Glenn Research Center. Pre-qualification testing of development HCAs as well as acceptance testing of the flight HCAs is presented. Integration of the HCAs into the Boeing North America built PCU and acceptance testing of the PCU are summarized in this paper. Finally, data from the two on-orbit PCUs is presented.

Introduction

Electron current collection by the high voltage solar arrays is expected to lead to charging of the International Space Station (ISS) habitat modules, structure and radiators. The high voltage solar arrays of the ISS power system are designed to operate at output voltages of typically 140 to 160 V. The negative tap of the ISS solar arrays is electrically tied to the habitat modules, structure, and radiators. With the solar arrays providing a large surface for electron current collection from the ambient space plasma, the ISS habitat modules, structure and radiators are predicted to float as much as 120 V negative with respect to the ambient space plasma potential [1]. If uncompensated, this large negative potential could lead to arcing through insulating surfaces on the ISS, ion bombardment resulting in sputter erosion of surfaces, as well as unsafe conditions for astronauts during extra-vehicular activities.

To mitigate the effect of these large negative voltages, a plasma contactor unit (PCU), which includes a hollow cathode assembly (HCA) current source, has been developed to actively control space station charging [1]. The HCA was chosen for its ability to emit copious electron current at low voltages and under variable demand. The high degree of reliability and long life of HCAs also make them desirable for the ISS PCU application.

HCA development at the NASA Glenn Research Center (GRC) has encompassed manufacture of engineering model, qualification model, and flight unit HCAs as well as extensive qualification and life testing of HCAs. The details of the HCA designed by GRC are given by Patterson [1]. The PCU HCA is a direct outgrowth of the ion thruster development program at GRC [2]. Two primary life tests of the HCA have been run. A single cathode life test reached 28,000 hours of operation before the cathode failed to ignite [3]. A four cathode life test was performed with a mission-like emission current profile that approximated the predicted demand from the ISS. One of the four cathodes was voluntarily stopped for destructive analysis [4]; the other three have reached from 12,000 to 19,000 hours of cathode operation [5].

Ignition testing of a flight-like cathode reached 42,000 ignitions before heater failure [6]. The cathode heater reliability has been the subject of testing as well [5,7].

This paper summarizes the performance of the two PCUs currently aboard the ISS and the efforts at GRC to develop and manufacture HCAs for the ISS PCU.

Description of the Plasma Contactor Unit

The space station PCU is a self-contained system providing power processing and expellant flow to generate a low impedance plasma bridge for spacecraft charge control. A photo of the ISS PCU is shown in Figure 1. The power processor includes separate power supplies for the HCA heater, keeper anode, and cathode ignitor. The PCU gas feed system provides high purity xenon expellant to the HCA at a fixed flow rate. Electron current emission is performed by the HCA itself.

The HCA design was chosen for its long life and effective, self-regulated operation under variable emission current demand. A drawing of the ISS HCA is shown in Figure 2. An enclosed keeper cathode was chosen since this configuration has been proven to efficiently provide a low voltage, electron current coupling to the ambient plasma. A small diameter orifice was employed on the downstream end of the cathode tube to increase internal cathode pressures for cathode operation, thereby reducing the expellant requirements for the PCU. A low work function, impregnated tungsten thermionic emitter insert was placed in the cathode tube at the downstream end to reduce cathode operating temperatures, to facilitate starting, and to produce the dense plasma in the cathode interior from which the HCA electron current is extracted. A cathode heater was included in the design to provide for fast, reliable HCA ignition and to evolve contaminants on the emitter surface after atmospheric exposure. The cathode assembly is fabricated largely from refractory metals and alloys for a rugged, durable assembly. Each of these components works together to yield a reliable and efficient electron source for the ISS PCU.

Requirements for the International Space Station

There are several requirements placed on an ISS plasma contactor system. An ISS plasma contactor system is required to control station charging to within +/- 40 V of ambient space plasma potential. The effect of v x **B** charging as the ISS moves through the earth's magnetic field tightens the requirement to within +/- 20 V of ambient space plasma potential. Additionally, practical requirements include long life, reliable ignition, and effective operation after environmental exposure during manufacture and integration [1].

Clamping voltage and emission current

The HCA must supply sufficient current to control the ISS potential with respect to the ambient space plasma potential. To meet this requirement, the HCA was restricted to an emission current of at least 10 A at less than 20 V. The peak emission current demand of the ISS is expected to be much less than 10 A [1].

HCA life and reliability

The HCA is also required to provide durable and reliable charge control for the ISS. HCA lifetime must meet or exceed 18,000 hours, which is the expected life of the PCU system given the PCU xenon storage capacity. PCU lifetime can be optionally extended by operating the HCA only during periods of active ISS charging. In order to facilitate this option, the HCA was required to be capable of 6000 ignitions with at least 99 percent reliability.

Hollow Cathode Assembly Integration into the Plasma Contactor Unit

Integration of the HCA into the Boeing developed PCU is supported by GRC engineers and technicians. Figure 3 shows a photo of an HCA installed in the third PCU manufactured by Boeing. This PCU will serve as a spare for the two PCUs currently on the ISS. Installation of the HCA into the PCU is supported by GRC technicians and connection of the HCA to the PCU gas feed system is performed by GRC technicians. Any issues which may arise during HCA installation are resolved cooperatively by Boeing and GRC engineers.

Ground Testing of Flight Hollow Cathode Assemblies

Each flight HCA was acceptance tested before delivery to Boeing by GRC. The acceptance test procedure includes a confidence test of the cathode heater and a plasma test. The heater confidence test consists of a 150 cycle burn-in and a hot resistance measurement to verify heater operation and workmanship. The plasma test includes a test in idle mode (with emission current to the keeper anode only) at several flow rates. Figure 4 shows the keeper anode voltage during acceptance testing as a function of flow rate for the flight cathodes. Note the high degree of repeatability between the newly fabricated cathodes. Additionally, a clamping mode test is run to verify that the cathode is capable of emitting at least 10 A of emission current at less than 20 V with a keeper anode current of 3 A. The cathodes were also ignited repeatedly to demonstrate that the cathodes are capable of a minimum of 10 ignitions in 6.0 minutes or less.

After integration of the HCA, the PCU is acceptance tested to demonstrate that the system is capable of meeting the ISS charge control requirements. The acceptance test includes 15 cathode ignitions, a clamping mode test, and a 24 hour test in idle mode. Results of the clamping mode tests for the QUAL, FM.01, FM.02, and FM.03 PCUs are shown in Figure 5. The upper bound on clamping voltage of the PCU is also shown to illustrate the performance of the PCU with respect to the ISS requirements.

Plasma Contactor Operation on the International Space Station

The PCUs FM.01 and FM.02 were delivered to the ISS in October 2000. The PCUs were carried to the ISS aboard space shuttle flight STS–92. Figure 6 shows the FM.01 and FM.02 installed on the ISS Z1 truss. FM.01 was first ignited aboard the ISS on October 27, 2000. FM.02 was ignited on November 17, 2000. Since that time FM.01 and FM.02 have undergone 10 ignitions each. Time to ignition for each of these ignitions is plotted in Figure 7. Time to ignition is defined as the time from the application of high voltage pulses between cathode and keeper to the time at which a 2.5 A current is measured at the keeper. Ignition times ranged from 2 seconds to 90 seconds; the time to ignition requirement for the PCU is 30 minutes. FM.01 and FM.02 have operated for accumulated times of 2123 hours and 2824 hours, respectively. Keeper anode potentials have ranged between 13.1 and 13.9 V. These keeper anode voltages and ignition times indicate that the two PCUs themselves are operating as expected.

Summary and Ongoing GRC Involvement

Efforts toward the development of HCAs by the NASA Glenn Research Center have been instrumental in the successful deployment and demonstration of the Plasma Contactor system on-board the International Space Station. Extensive testing of the PCU HCAs has been conducted at GRC to address issues of life, reliability, and cathode operation [5]. The eventual outcome of this testing was a finalized design for the HCA used in the ISS PCU system. To date, twelve flight HCAs have been built by GRC and rigorously acceptance tested. A total of three of these HCAs have been installed and tested in flight PCUs, and currently FM.01 and FM.02 PCUs are providing charge control upon the International Space Station. FM.01 and FM.02 are both operating as expected with 10 ignitions each and a total of 2123 hours and 2824 hours of accumulated operating time, respectively. The third PCU, FM.03, has been acceptance tested, and is available as a spare for the two units already on-orbit.

NASA Glenn Research Center continues to support the ISS plasma contactor program in a number of ways. Life testing of three flight-like HCAs in a mission-like, cyclical profile is continuing until the life test articles have reached 1.5 times their rated life. Integration of the HCA into the Boeing developed PCU is also supported by GRC engineers and technicians. Flight model PCU acceptance testing to verify the charge control capabilities of the completed system is performed at GRC in its world class vacuum facilities. HCAs with reduced requirements for expellant flow are also being developed at GRC as an option to extend the operating life of on-orbit PCUs.

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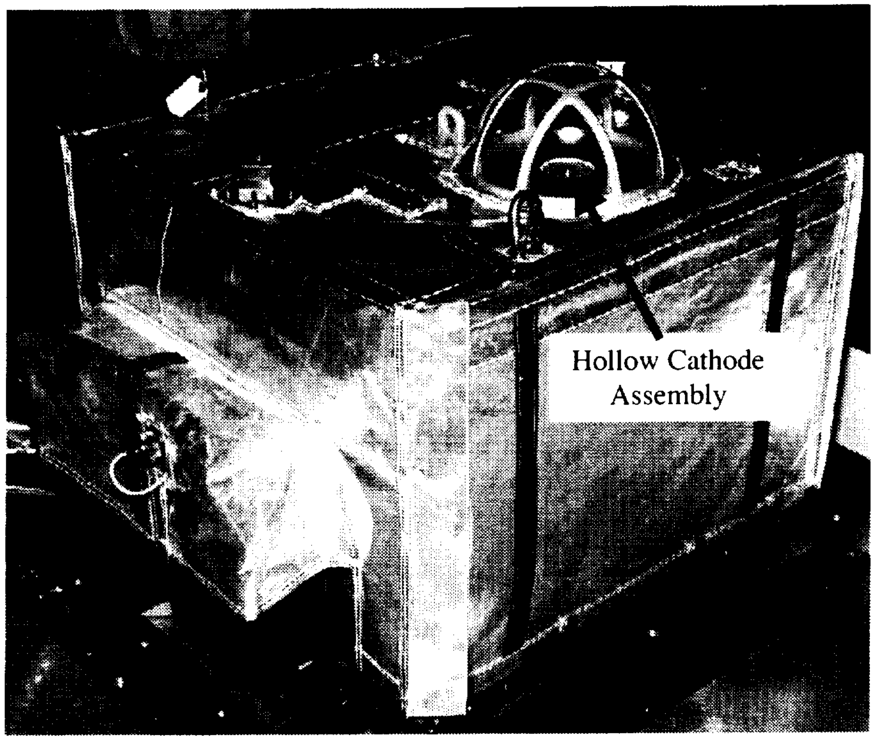

Figure 1. Photo of an ISS flight model PCU. The PCU is covered by a multi-layer insulation blanket. The HCA has been pointed out in the image.

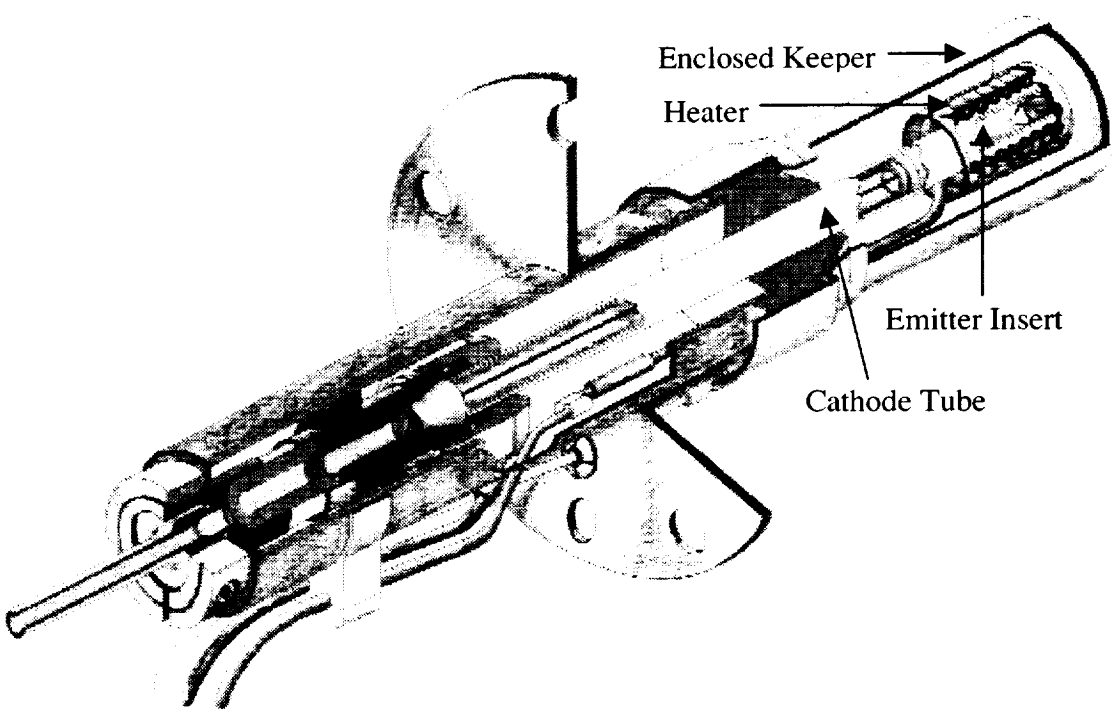

Figure 2. Drawing of a flight HCA (drawing not to scale).

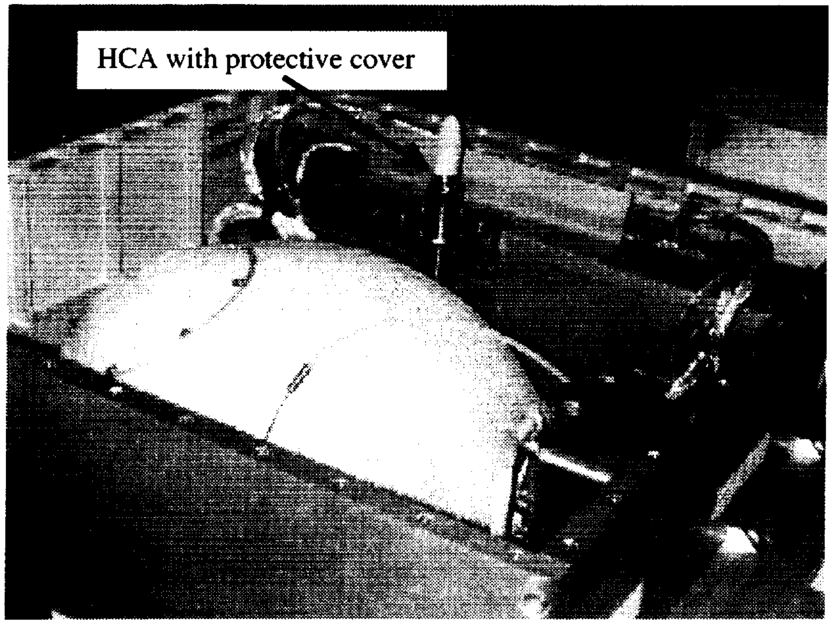

Figure 3. Photograph of flight HCA.004-F being integrated into the ISS PCU box. Image shows the PCU with its top cover removed. The large white sphere is the xenon storage tank. The HCA is pointed out in the picture.

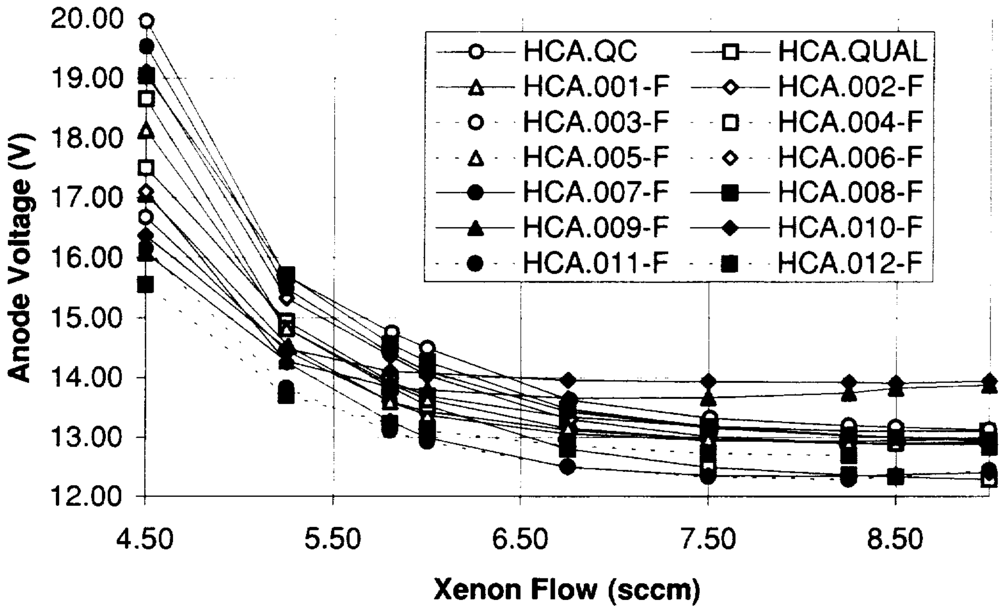

Figure 4. Flight HCA keeper anode voltage in idle mode, as a function of flow rate, during HCA acceptance testing.

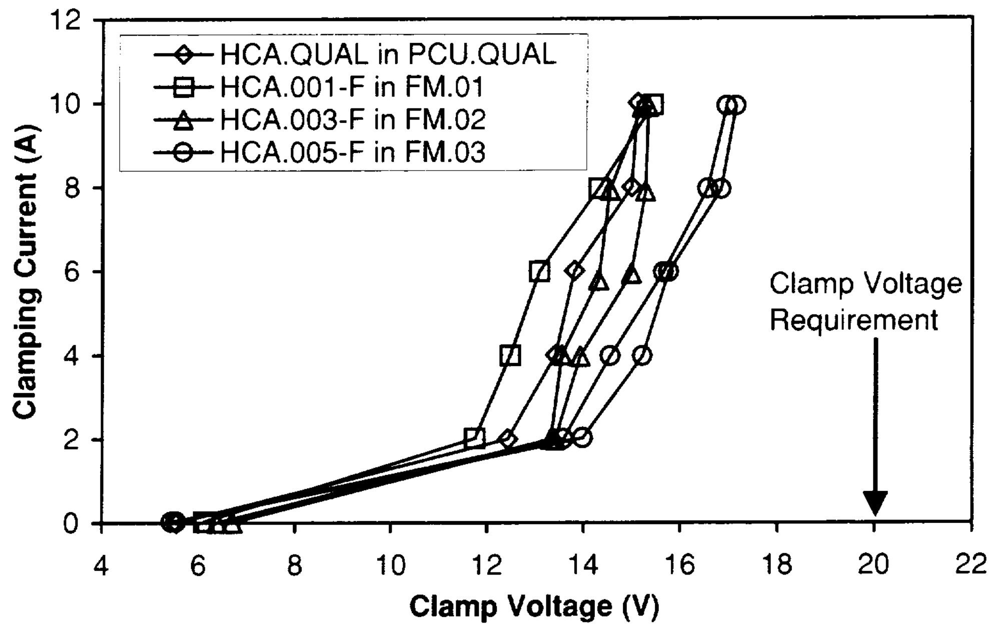

Figure 5. Clamping voltages of the PCUs QUAL, FM.01, FM.02, and FM.03 during flight PCU acceptance testing at NASA Glenn Research Center. Performance in the GRC vacuum facility is expected to match performance on-orbit.

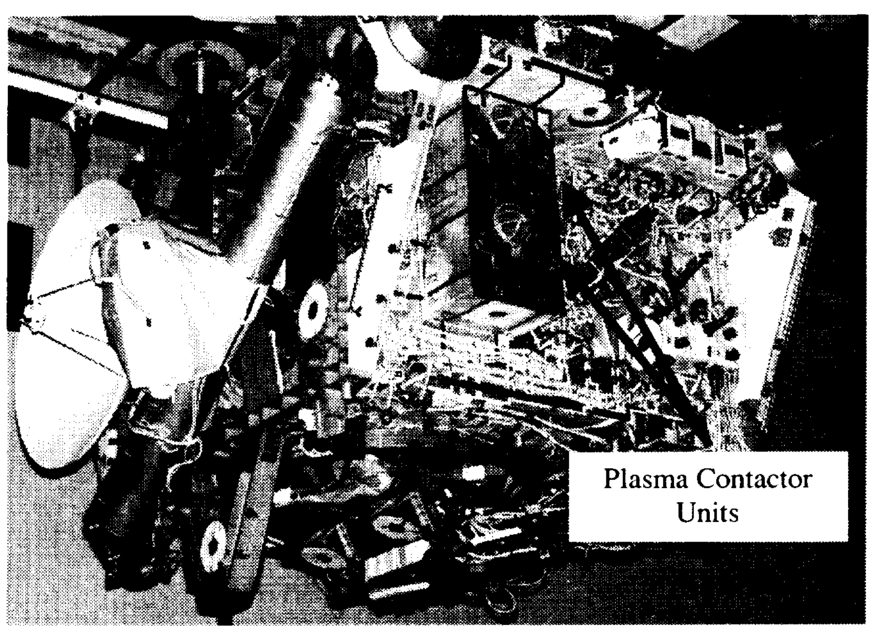

Figure 6. PCUs FM.01 and FM.02 installed on the ISS Z1 truss.

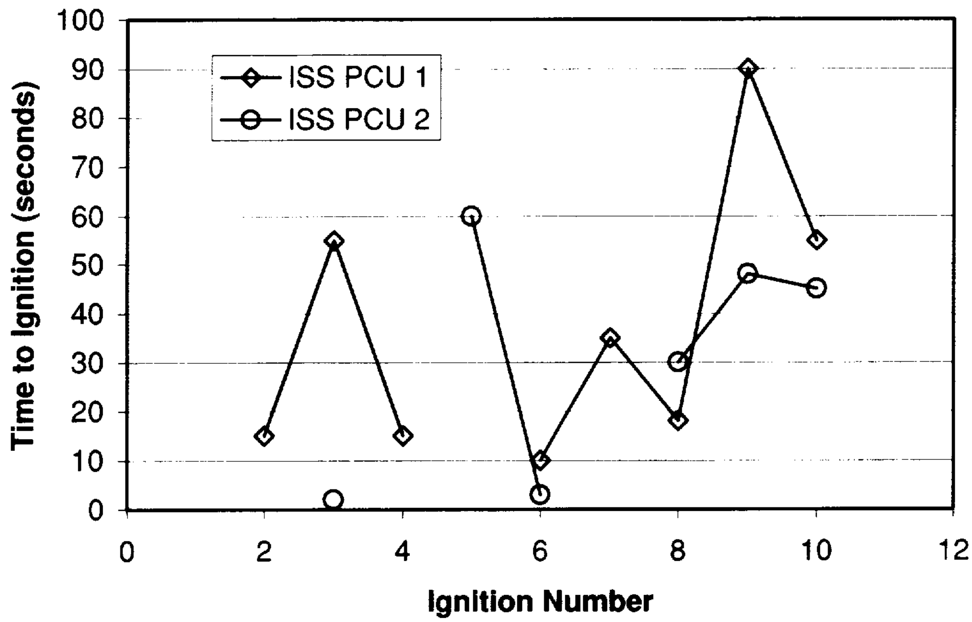

Figure 7. Time to ignition for on-orbit ignitions of PCU 1 and PCU 2 (the FM.01 and FM.02 PCUs). A gap indicates time to ignition data was not obtained for that ignition.

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13. ABSTRACT ***(Maximum 200 words)***

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